# FINAL TECHNICAL REPORT

# Digital Compilation of Thrust and Reverse Fault Data for the Northern California Map Database: Collaborative Research with William Lettis & Associates, Inc., and the U.S. Geological Survey

**Recipient:**

William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262, Walnut Creek CA 94596
Phone: (925) 256-6070 Fax: (925) 256-6076
URL: www.lettis.com

**Principal Investigators:**

Jeffrey Unruh and Sean Sundermann
Email: unruh@lettis.com; sundermann@lettis.com

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# DIGITAL COMPILATION OF THRUST AND REVERSE FAULT DATA FOR THE NORTHERN CALIFORNIA MAP DATABASE: COLLABORATIVE RESEARCH WITH WILLIAM LETTIS & ASSOCIATES, INC., AND THE U.S. GEOLOGICAL SURVEY

Jeff Unruh and Sean Sundermann

William Lettis & Associates, Inc.
1777 Botelho Drive, Suite 262, Walnut Creek CA 94596
Phone: (925) 256-6070 fax: (925) 256-6076
Email: unruh@lettis.com; sundermann@lettis.com

## ABSTRACT

This study presents a new digital map compilation of Quaternary thrust faults and folds in the eastern San Francisco Bay region. The work described herein is part of a collaborative effort between private and academic geologists and U.S. Geological Survey (USGS) to construct a Quaternary fault map and database for the San Francisco Bay area, with a target publication date of April 2006. This new compilation of Quaternary thrust and reverse faults revises and builds on previous work by the USGS (Jayko et al., 1996), and on the 1999 Northern California Working Group characterization of active thrust and reverse faults in the San Francisco Bay area. By explicitly incorporating blind thrust and reverse faults, the new Quaternary fault map compilation and database will be a significant step forward in identifying and characterizing potential sources of moderate-magnitude "background" earthquakes in urbanized areas of northern California.

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## 1.0 INTRODUCTION

The goal of this study is to compile map and geologic data on active thrust faults in a digital format for the Northern California Quaternary Fault Map Database (NCQFMD). This study is a collaborative effort with other researchers, and is being coordinated by Dr. Russell Graymer of the U.S. Geological Survey (Menlo Park). In an email communication dated 11 November 2004, Dr. Graymer outlined his research priorities for participants in the NCQFMD project as follows:

1) Provide “fault traces in GIS”;
2) Evaluate “fault strand rank”;
3) Evaluate “location uncertainty:’
4) Characterize “geomorphic expression”; and
5) Compile “site-specific point data”.

The primary regions of interest for this effort include parts of the East Bay hills, the northern Diablo Range, the Sacramento-San Joaquin Delta region, the southwestern Sacramento Valley, and the Howell Mountains east of Napa Valley. Geologic mapping of Quaternary folds and thrust faults in these regions was compiled at the largest available scale and, where necessary, digitized and georeferenced. The metadata description of the mapping is presented in Section 3 of this report.

## 2.0 MAP DEPICTION OF BLIND THRUST FAULTS

By definition, "blind thrust faults" have no surface trace, and thus any map depiction must be some type of surface projection of the fault, a surface manifestation of slip at depth, or an abstract representation. We considered several different approaches to depicting blind thrust faults on a map:

1) *Blind fault tip line*. If known, the location of the buried tip of a blind thrust fault can be shown in plan view as a line. Additional data to fully characterize the tip line and blind thrust fault (such as: depth to the tip line; fault dip; fault width; etc) can be incorporated as attributes in the digital database.

2) *Intersection of the updip projection of the fault with the land surface*. If the location and dip of a blind fault at depth are known, but the precise location of the fault tip cannot be determined, then the intersection of the up-dip projection of the fault plane with the earth's surface can be plotted as a line.

3) *Intersection of the fault with a subsurface stratigraphic horizon.* In some cases, blind thrust faults may be identified and mapped through analysis and correlation of stratigraphic units encountered in exploration wells. Thrust (and normal) fault offsets can be shown as lines of discrete offset in structure contours of stratigraphic horizons. These lines are plan projections of the intersection of the fault with the stratigraphic horizon at depth.

4) *Active fold scarp*. Coseismic slip on a blind thrust fault may result in discrete uplift, tilting and folding of the hangingwall block. Depending on the kinematic style of fold growth, this surface deformation may be localized along the bases of the fold limbs. For example, fault-propagation fold models (e.g., Suppe and Medwedeff, 1984) predict incremental uplift and tilting at the bases of the fold forelimb and backlimb, which could potentially produce a discernable topographic scarps. In fault-propagation fold models, an inclined axial surface at the base of the fold forelimb links the escarpment at the surface with the tip of the blind thrust fault at depth. The base of a fold scarp is a mappable feature that is kinematically related to the tip of the blind thrust fault at depth.

5) *Syncline axis corresponding to the base of a fold forelimb*. A reductionist description of a syncline in a fold-thrust belt is that it marks the boundary between two anticlines. For example, if there are two or more large anticlines separated by synclines, and each anticline is associated with a discrete blind thrust fault or thrust ramp at depth, then the surface trace of the syncline axis can be interpreted as the maximum subsurface extent of the corresponding blind thrust fault or ramp in the direction of fold and fault vergence. If a blind thrust fault can be reasonably inferred to exist beneath an asymmetric anticline, but its depth and dip are very uncertain, then the likely presence of the fault and its interpreted sense of vergence can be depicted on a map by flagging or attributing the syncline axis that marks the base of the fold forelimb. A fold scarp (see above) is a special case where there is geomorphic evidence of uplift localized along the synformal hinge at the base of the fold forelimb.

Ideally, we would prefer to map the tip line of a blind thrust fault (Approach 1, above), and fully characterize the depth to the fault tip, the dip of the fault, the downdip extent of the fault (i.e., the branchline at the base of the seismogenic crust) with attributes in the digital database. This information would permit workers to construct well-constrained 3-D models of the blind thrust fault from the map data. Detailed mapping of thrust fault tip lines is only practical, however, in areas where seismic reflection or other subsurface data are available to permit confident interpretation and characterization of blind thrust faults. In general, this is not the case in the eastern San Francisco Bay area.

Mapping the intersection of the up-dip projection of a blind thrust fault with the earth's surface (Approach 2) is a viable alternative if the location and general subsurface geometry of the fault can be determined with some confidence, but the location of the fault tip is poorly constrained. The value of this approach is that it provides map information that can be used in some empirical approaches for calculating directivity effects on seismic ground motions. In areas where there are sufficient subsurface data to identify thrust-fault offset of stratigraphic horizons, Approach 3 above can be used to show the plan view projections of faults at a given depth and stratigraphic horizon. Additional information on the depth to the fault from the well data can be included as an attribute in the GIS database. The value of depicting an active fold scarp (Approach 4) is that the line on the map shows potential locations of coseismic surface deformation, and conveys information about the likely dip and vergence of the blind thrust fault (Approach 5).

For this project, we have used a combination of the five approaches above to depict Quaternary blind thrust faults in the eastern San Francisco Bay area. The use of a particular approach is dictated by available data on the thrust fault and associated fold or surface deformation.

## 3.0 METADATA

The database was compiled in ArcGIS 8.3, a Geographic Information System created by Environmental Systems Research Institute (ESRI, Redlands, California). The comprehensive database consists of the thrust and reverse fault compilation database, supporting metadata, and this report. The fault map database consists of one ARC shapefile (EBayarea_thrustfaults.shp), which was created and attributed according to the NCQFMD format for incorporation into the Bay Area Quaternary fault map database.

The map traces of these structures were compiled at the largest available scale from published and unpublished sources. We compared the compiled fault traces with published CGS Official Maps of Alquist-Priolo Earthquake Fault Zones and the "Fault Traces of California Map" (1994) by Charles Jennings. Where necessary, we made minor revisions to the fault traces for continuity. The compilation includes the following sources:

**Table 1. Data Sources**

| **Geographic Area** | **Source** |
|---|---|
| Anticlines in Napa County | Baldwin, J., Unruh, J.R. and Lettis, W. (1998) |
| Pittsburgh Fault | Williams, P. (2004) |
| Livermore Valley | Sawyer, T. (2004) |
| Southwestern Sacramento Valley | O'Connell, D.R.H., Unruh, J.R., and Block, L.V. (2001) |
| Midland Fault | Jennings, C. (1994) |
| Thrust faults and folds in Contra Costa and Alameda Counties | Crane, R. (1988; geologic maps of numerous 7.5' quadrangles) |
| Los Medanos Hills Thrust System | Hoffman (1992), with modification by Unruh, J.R. and Hector, S. (1999) |
| Carquinez Strait-Suisun Bay area | Unruh, J.R. and Hector, S. (1999) |

Our priority for mapped traces was the most up-to-date state of knowledge at the largest scale possible. As a result, our preference for interpretive analysis was digital GIS files followed by original manuscripts and finally published stable originals. Digital files were compiled from the source author for the Livermore Valley and the Midland Fault. Communication between ourselves and Tom Sawyer was ongoing throughout the mapping process to ensure accuracy in interpretation. Where possible, original WLA map manuscripts (i.e. "lead on mylar") were used for compilation, including the Los Medanos Hills Thrust System, Pittsburgh-Kirby Hills Fault Zone and Napa County Anticlines. Published maps were utilized for West Contra Costa County, Southwestern Sacramento Valley, and the Pittsburgh Fault (with additional updates from John N. Baldwin based on current work).

Stable source maps were scanned using a large-format color scanner with a resolution of 600 dots per inch. The scanned maps were georeferenced into our working coordinate system for vectorization using the Georeferencing extension in ArcGIS 8.3. Georeferencing was accomplished with control points linked to map edge tics and cultural features in a heads-up digitization process. The link table was intentionally saturated to facilitate sub-meter root mean square horizontal error. The georeferenced maps were vectorized using heads-up digitization and drawn as accurately as possible at the map scale of 1:24,000. Attribute tables were completed within GIS and follow the NCQFMD format.

Vectorized maps and the acquired digital files were compiled at a map scale of 1:24,000. Although the digital format of the dataset permits viewing the data at a larger scale, the detail and accuracy of the drawing is compromised at any scale larger than 1:24,000. Viewing the data at a larger scale will not generate any greater detail than that presented at the original scale and should not be used for investigations requiring greater detail.

## 4.0 SUPPLEMENTAL DATA

This section provides additional explanation of the characterization of blind faults and their attribution in the GIS database.

### 4.1 The Las Trampas Anticline and Associated Blind Thrust Fault, Northern East Bay Hills

Fault strand rank = 1

Location certainty, Las Trampas anticline axis = 2. Fold axis and fold asymmetry are moderately well defined by strike and dip data on compilation map of the Las Trampas 7.5' quadrangle by Crane (1998).

Location certainty, blind Las Trampas thrust fault = 3. Based on analysis of fold asymmetry, Unruh and Kelson (2002) interpreted that the anticline is underlain by a blind, southwest-dipping thrust fault. The precise location of the fault tip at depth is not known, nor are the dip and potential rupture width of the fault. Given this uncertainty, no fault is mapped.

Geomorphic expression: Las Trampas Ridge is a prominent, local topographic high associated with Las Trampas anticline (Unruh and Kelson, 2002).

Notes and References: Unruh and Kelson (2002) proposed that the Las Trampas anticline may reflect local shortening due to transfer of dextral slip from the northern Calaveras fault in a left-restraining step to the Lafayette fault in the interior of the East Bay hills.

Unruh, J.R., and Kelson, K.I., 2002, Critical Evaluation of the Northern Termination of the Calaveras Fault, Eastern San Francisco Bay Area, California: Final Technical Report submitted to U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award Number 00-HQ-GR-0082, 72 p. plus oversize plate.

### 4.2 Tice Anticline

Fault strand rank = 2

Location certainty, Tice anticline axis = 3. Fold axis is inferred from changes in dip of Paleogene and late Neogene strata on Crane's (1988) geologic maps of the Las Tramps Ridge and Walnut Creek 7.5' quadrangles (note: Crane (1988) does not explicitly show a fold axis associated with the bedding dip changes on these maps). Anticline appears to deform mapped fault contact between Eocene and Miocene strata east of Tice Valley.

Location certainty, blind Tice anticline thrust fault = 3. The inferred Tice anticline may be underlain by a blind, southwest-dipping thrust fault. The precise location of the blind fault tip at depth is not known, nor are the dip and potential rupture width of the fault.

Geomorphic expression: The Tice anticline has a right-stepping geometry relative to the Las Trampas anticline to the southwest (Section 4.1). The hill associated with the Tice anticline is shorter and has less topographic relief than Las Trampas Ridge, which may indicate less cumulative slip and/or a lower slip rate on an underlying thrust fault.

Notes and References: The Tice anticline, if present, may be related to the restraining transfer of dextral slip from the Calaveras fault to the interior of the East Bay hills inferred by Unruh and Kelson (2002).

Unruh, J.R., and Kelson, K.I., 2002, Critical Evaluation of the Northern Termination of the Calaveras Fault, Eastern San Francisco Bay Area, California: Final Technical Report submitted to U. S. Geological Survey, National Earthquake Hazards Reduction Program, Award Number 00-HQ-GR-0082, 72 p. plus oversize plate.

### 4.3 Verona Thrust Fault

Fault strand rank = 2. Sawyer and Unruh (in progress) interpret that the Verona thrust fault may splay upward from a blind, northeast-dipping thrust fault that extends southwest of the Vallecitos Hills in the subsurface, and which underlies a southwest-vergent anticline.

Location certainty = 1

Geomorphic expression: The Verona fault is mapped at or near the southwestern front of the Vallecitos Hills, which have been uplifted in Quaternary time as evidenced by tilting of the late Pleistocene Livermore Gravels on the northeast side of the hills. Sawyer and Unruh (in progress) also observed field evidence for uplift of Quaternary stream valleys in the hanging wall of the fault.

Notes and References: Field observations and exploratory trenching described by Herd and Brabb (1980) provide a prima facie case for late Quaternary surface rupture on the fault.

Herd, D.G., and Brabb, E.E., 1980, Faults at the General Electric test reactor site, Vallecitos Nuclear Center, Pleasanton, California: A summary review of their geometry, age of last movement, recurrence, origin, and tectonic setting and the age of the Livermore Gravels: U.S. Geological Survey Administrative Report, 77 p.

### 4.4 Williams Thrust Fault

Fault strand rank: 1

Location certainty: 1

Geomorphic expression: Fault is mapped adjacent to the northwest-trending Williams Gulch in the northern Diablo Range.

Notes and References: The Williams fault is located approximately on strike to the southeast of the Verona fault and has a similar dip direction, but is separated in a right-lateral sense from the Verona fault across the sinistral Las Positas strike-slip fault. Although it is possible that the Williams and Verona faults splay upward from a common northeast-dipping thrust fault at depth, independent data on the Quaternary activity of the Williams fault currently is not available.

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of Blind Seismogenic Sources, Livermore Valley, Eastern San Francisco Bay Region: final technical report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-95-G-2611.

### 4.5 Livemore Thrust Faults

#### *4.5.1 Livemore Thrust Fault 1 (blind)*

Fault strand rank = 2

Location certainty = 3

Geomorphic expression: Activity of the fault and associated uplift of the hanging wall block may have deflected the course of Arroyo Valle during late Quaternary time (T. Sawyer, personal communication, 2005).

Notes and References: Digital fault traces provided by T. Sawyer of Piedmont Geosciences from work in progress.

#### *4.5.2 Livemore Thrust Fault 2 (blind)*

Fault strand rank = 2

Location certainty = 3

Geomorphic expression: Activity of the fault and associated uplift of the hanging wall block may have deflected the course of Arroyo Valle during late Quaternary time (T. Sawyer, personal communication, 2005).

Notes and References: Digital fault traces provided by T. Sawyer of Piedmont Geosciences from work in progress.

### 4.6 Pleasanton Fault 1 (blind)

Fault strand rank = 2

Location certainty = 3

Geomorphic expression: Activity of the fault and associated uplift of the hanging wall block may have deflected the course of Arroyo Valle during late Quaternary time (T. Sawyer, personal communication, 2005).

Notes and References: Digital fault traces provided by T. Sawyer of Piedmont Geosciences from work in progress.

### 4.7 Mt. Diablo Thrust Fault (blind)

The peak of Mt. Diablo is the topographic culmination of the northwest-trending Mt. Diablo anticline, a southwest-vergent fold located in a restraining step between the dextral Greenville and Concord faults. Unruh and Sawyer (1997) proposed that Mt. Diablo anticline is a fault-propagation fold developed above a blind, northeast-dipping thrust fault. Based on variations in the geometry of the fold along trend, it is possible that the Mt. Diablo thrust fault is divided into at least two structural segments that are offset in a right-stepping sense. The two segments are informally referred to herein as the “northwest segment” and “southeast segment”. The structural boundary between the two segments is interpreted to be near the town of Alamo, and is spatially associated with a northeast-trending alignment of earthquakes informally called the “Alamo swarm” (Oppenheimer and Macgregor-Scott, 1992).

#### *4.7.1 Mt. Diablo Thrust Fault (blind)—Southeast Segment*

Fault strand rank = 1

Location certainty = 2. Based on analysis of old, proprietary seismic reflection data, the tip line of the blind Mt. Diablo thrust fault may be present at a depth of several kilometers either directly below or slightly northeast of the southwestern front of the Tassajara hills (Unruh, 2000). The tip line of the fault may shallow toward the northwest as the Tassajara anticline plunges out toward the northwest.

Geomorphic expression: Mt. Diablo and Tassajara anticlines are interpreted to be the surface expression of slip at depth on the blind Mt. Diablo thrust fault (Crane, 1995; Unruh and Sawyer, 1997). The abrupt southwestern front of the Tassajara hills is underlain by subvertical to very steeply west-dipping Pleistocene strata, and may be a fold scarp above the fault tip. The front of the hills in eastern San Ramon Valley may be a fold scarp that has been modified by fluvial erosion.

Notes and References:

Oppenheimer, D.H., and Macgregor-Scott, N., 1992, The seismotectonics of the eastern San Francisco Bay region, *in* Borchardt, G., Hirschfeld, S.E., Lienkaemper, J.J., McClellen, P., Williams, P.L., and Wong, I.G., eds., Proceedings of the Second Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 113, p. 11-16.

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of Blind Seismogenic Sources, Livermore Valley, Eastern San Francisco Bay Region: final technical report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-95-G-2611.

Unruh, J.R., 2000, Characterization of Blind Seismic Sources in the Mt. Diablo-Livermore Region, San Francisco Bay Area, California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-HQ-97-GR-03146.

### *4.7.2 Mt. Diablo Thrust Fault (blind)—Northeast Segment*

Fault strand rank = 1

Location certainty = 3. Based on construction of restorable cross sections, the tip line of the northeast segment of the Mt. Diablo thrust fault may be present at a depth of several kilometers either directly below or slightly northeast of the syncline axis at the base of the fold forelimb (Unruh, 2000) located southwest of Shell Ridge in Walnut Creek. Rather than mapping a very speculative and uncertain blind tip line in this region, we have attributed the syncline axis to indicate the presence and vergence of the underlying thrust fault (following approach 5 described in Section 1).

Geomorphic expression: Shell Ridge, a prominent high-standing strike ridge in eastern Walnut Creek, is underlain by overturned Neogene sandstone in the forelimb of Mt. Diablo anticline. The topography and relief of Shell Ridge increase significantly east of the syncline axis we have attributed to indicate the presence of the blind Mt. Diablo thrust fault, suggesting that the entire ridge may be a large fold scarp.

Notes and References:

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of Blind Seismogenic Sources, Livermore Valley, Eastern San Francisco Bay Region: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-95-G-2611.

Unruh, J.R., 2000, Characterization of Blind Seismic Sources in the Mt. Diablo-Livermore Region, San Francisco Bay Area, California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-HQ-97-GR-03146.

## 4.8 Sherburne Hills thrust faults

Fault strand rank = 2

Location certainty = 1. Modified from Crane (1988) based on air photo interpretation of T. Sawyer (T. Sawyer, personal communication, 2005).

Geomorphic expression: Mapped fault traces are associated with air photo lineaments (T. Sawyer, personal communication, 2005).

Notes and References: The informally named Sherburne Hills thrust faults are located above the inferred tip of the blind Mt. Diablo thrust fault, but a connection between the two structures, if any, is not well understood. The Sherburne Hills faults may have formed by out-of-syncline thrusting in tight, closely spaced, short wavelength folds above the (shallowing?) tip of the Mt. Diablo thrust fault. Alternatively, these faults may represent emergence of the tip of the Mt. Diablo thrust fault.

## 4.9 Doolan Anticline

Fault strand rank = 2

Location certainty of fold axis = 2

Notes and References: Doolan anticline is one of several short-wavelength, closely spaced folds mapped by Crane (1988) on the forelimb of Tassajara anticline. The Doolan anticline and associated folds are subparallel to, and generally on trend with, the Sherburne Hills thrust faults to the northwest.

## 4.10 Highlands School anticline

Fault strand rank = 2?

Location certainty = 1

Geomorphic expression: Antiformal fold in the tread of a late Pleistocene fluvial terrace near the site of Highland School (abandoned) in the southern part of the USGS Tassajara 7.59 quadrangle (SE 1/4 sec. 12, T.2S., R.1E.). Folding is expressed as a distinct convexity in the longitudinal profile of the terrace, and has produced local backtilting of the terrace tread and ponding of late Pleistocene sediment behind the fold axis (T. Sawyer, 1999; also, personal communication, 2006).

Notes and References: Deflection of tread surface is documented by detailed surveying (T. Sawyer, personal communication, 2006).

Sawyer, T.L., 1999, Assessment of contractional deformation rates of the Mt. Diablo fold and thrust belt, eastern San Francisco Bay Region, Northern California: Final Technical Report submitted to the U.S. Geological Survey National Earthquake Hazards Reduction Program, Award No. 98-HQ-GR-1006, 53 p.

## 4.11 East Tassajara Anticline and Underlying Blind Thrust Fault

Fault strand rank = 1

Location certainty = 1

Geomorphic expression: Fold axis reasonably well constrained by strike and dip data (Crane, 1998)

Notes and References: Anticline is associated with a NW-trending line of low hills in eastern Livermore basin (T. Sawyer, work in progress, personal communication 2005.

### 4.12 Springtown Anticlines and Underlying Blind Thrust Fault

Fault strand rank = 2. Sawyer and Unruh (in progress) interpret that a blind, west-dipping thrust fault underlies the eastern margin of the Springtown anticlines. If this interpretation is correct, the fault probably is rooted in a deeper east- to northeast-dipping thrust fault.

Location certainty = 3. The location of the tip of the interpreted west-dipping blind thrust fault beneath the Springtown anticlines is not directly constrained by available data. Based on the fold geometry, the tip of the blind thrust fault probably lies beneath or slightly west of the abrupt eastern front of the hills (Sawyer and Unruh, in progress), which may be a fault or fold scarp.

Geomorphic expression: The morphology of the Springtown hills directly reflects the geometry of the folds; i.e., the hills are associated with anticlines, and the intervening valleys are associated with synclines (Unruh and Sawyer, 1997).

Notes and References:

Unruh, J.R., and Sawyer, T.L., 1997, Assessment of Blind Seismogenic Sources, Livermore Valley, Eastern San Francisco Bay Region: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program, Award no. 1434-95-G-2611.

### 4.13 Livermore Anticline and Thrust Fault

Fault strand rank = 2. Sawyer and Unruh (in progress) interpret that the blind Livermore anticline thrust fault likely splays upward from a deeper northeast-dipping thrust fault that underlies much of Livermore basin. Currently, there are no data to test the hypothesis that copseismic slip on the Livermore thrust fault, and consequently growth of the Livermore anticline, occurs independently of other fold-thrust structures in Livermore Valley.

Location certainty, Livermore anticline = 2. Due to the young age and poorly bedded character of the deformed sediments, as well as limited exposures, the axis of the fold is not well defined by bedding orientations. Dipmeter data from the “Wagoner #1” well drilled on or just west of these hills (precise location of the well is not known) confirm an antiformal closure at depth (Unruh and Sawyer, in progress). For the purposes of this map, the axis of the Livermore anticline is estimated to coincide with the axis of an associated line of hills.

Location certainty, Livermore thrust fault = 3. Livermore anticline is interpreted by Sawyer and Unruh (in progress) to be an asymmetric, west-vergent fault propagation fold developed above a blind, east-dipping thrust fault.

Geomorphic expression: The Livermore anticline coincides with a low line of hills underlain by uplifted Pleistocene Livermore Gravels. Wind gaps across the hills, associated with successive defeats of Arroyo Mocho, provide evidence for Quaternary growth of the anticline by northward propagation (T. Sawyer, personal communication, 2005).

Notes and References: Digital fault traces provided by T. Sawyer of Piedmont Geosciences from work in progress.

**4.14 Concord Anticline and Thrust Fault (blind)**

Fault strand rank = 1

Location certainty, anticline axis and thrust fault = 2. Anticline axis and fault trace transferred from 1:76,800-scale structure contour map on top of Domengine Formation in Hoffman (1992); Hoffman's map was constructed from analysis of gas exploration well data. Hoffman's cross sections indicate that the minimum depth to the fault tip beneath the anticline is about 610 m (2000 ft), and possibly as deep as 1.2 km (4000 ft).

Geomorphic expression: Anticline is associated with a line of low, northwest-trending hills that pass through the city of Concord.

Notes and References:

Hoffman, R.D., 1992, Structural geology of the Concord area, *in* Cherven V.B., and Edmondson, W.F., eds., The Structural Geology of the Sacramento Basin: Annual Meeting, Pacific Section, American Association of Petroleum Geologists, Volume MP-41, p. 79-90.

**4.15 City of Concord Anticline and Thrust Fault (blind)**

Fault strand rank = 2

Location certainty, anticline axis and thrust fault = 3. Anticline axis and fault trace transferred from 1:76,800-scale structure contour map on top of Domengine Formation in Hoffman (1992); map constructed from analysis of gas exploration well data.

Geomorphic expression: Unlike the Concord anticline (Section 4.13), the City of Concord anticline has no obvious geomorphic expression. The fold trace and associated thrust fault are mapped in a marshy region directly south of the Sacramento River.

Notes and References:

Hoffman, R.D., 1992, Structural geology of the Concord area, *in* Cherven V.B., and Edmondson, W.F., eds., The Structural Geology of the Sacramento Basin: Annual Meeting, Pacific Section, American Association of Petroleum Geologists, Volume MP-41, p. 79-90.

**4.16 Los Medanos Hills Thrust Fault Zone (blind)**

Fault strand rank = 2. Faults in Los Medanos Hills thrust zone interpreted by Unruh and Hector (1999) to splay upward from deeper thrust fault that projects updip to the Concord anticline southwest of the Los Medanos hills (see Section 4.14 above).

Location certainty =2. Locations of fault splays transferred from 1: 76,800-scale map in Hoffman (1992). Faults shown on a structure contour map of the upper surface of the Eocene Domengine Formation, which is located at depths of 610 m to 2130 m (2000 ft to 7000 ft) beneath the Los Medanos hills. Traces on the map thus represent the plan projection of faults from depth.

Geomorphic expression: Some of the faults identified in the subsurface by Hoffman (1992) project to surface faults mapped in the Los Medanos hills by Crane (1998). The traces of the surface faults locally are associated with small valleys, swales and ridges, which may be a function of the juxtaposition of rocks of different erosional character by the faults.

Notes and References: Named "Los Medanos thrust zone" by Hoffman (1992) to encompass numerous closely spaced northeast-dipping thrust faults in the Los Medanos hills. Hoffman's cross sections suggest either a back-breaking imbricate pattern for the faults, or complex cross-cutting relations in the core of the Los Medanos hills anticlinorium (Unruh, 2001). Hoffman's mapping indicates that lateral continuity of the thrust faults is interrupted by northeast-striking high-angle tear faults or accommodation zones.

Hoffman, R.D., 1992, Structural geology of the Concord area, *in* Cherven V.B., and Edmondson, W.F., eds., The Structural Geology of the Sacramento Basin: Annual Meeting, Pacific Section, American Association of Petroleum Geologists, Volume MP-41, p. 79-90.

Unruh, J.R., 2001, Characterization of Blind Thrust Faults in the San Francisco Bay Area, *in* Ferriz, H. and Anderson, R., Engineering Geology Practice in Northern California": California Geological Survey Bulletin 210, p. 211-227.

### 4.17 Roe Thrust Fault (blind)

Fault strand rank = 1

Location certainty = 2. Fault penetrated by the State "3741.1" well at a depth of about 3000 ft (Unruh and Hector, 1999). Trace shown on map is the intersection of the updip projection of fault with sea level. Horizontal location certainty is estimated to be about 1000 ft.

Geomorphic expression: None

Notes and References:

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

### 4.18 Roe Island Thrust Fault (blind)

Fault strand rank = 2

Location certainty = 2. Map trace is the plan projection of the intersection of the fault with the Domengine sandstone at a depth of about 3000 ft. Additional constraints on interpreted fault-fold geometry in Unruh and Hector (1999) from analysis of proprietary seismic reflection data.

Geomorphic expression: Roe Island may be exposed above water due to slip on the Roe Island thrust fault or structurally underlying Roe thrust fault.

Notes and References:

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

### 4.19 Ryer Island Thrust Fault (blind)

#### *4.19.1 Ryer Island Thrust Fault (blind) 1*

Fault strand rank = 2

Location certainty = 2. Map trace is the plan projection of the intersection of the fault with the Domengine sandstone at a depth of about 6000 ft.

Geomorphic expression: Ryer Island may be exposed due to slip on the Ryer Island thrust fault or structurally underlying Roe thrust fault. Additional constraints on fault-fold geometry from proprietary industry reflection data (Unruh and Hector, 1999).

Notes and References:

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

#### *4.19.2 Ryer Island Thrust Fault (blind) 2*

Fault strand rank = 2

Location certainty = 2. Trace on map is the plan projection of the intersection of the fault with the Domengine sandstone at a depth of about 6000 ft.

Geomorphic expression: Ryer Island may be exposed due to slip on the Ryer Island thrust fault or structurally underlying Roe thrust fault.

Notes and References:

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

### 4.20 Grizzly Island Thrust Fault

Fault strand rank = 2. Preferred interpretation of the Grizzly Island thrust fault is that it dips southwest and intersects the northeast-dipping Roe thrust fault well above the base of seismicity in this region. In this model, the Grizzly Island thrust fault accommodates shortening of the hanging wall of the Roe thrust fault, and thus is subordinate to the Roe thrust fault.

Location certainty = 2. Mapped trace is the plan projection of the intersection of the fault with the Domengine sandstone at a depth of about 6000 ft. The thrust fault is penetrated by at least two wells in the Grizzly Island gas field at depths ranging from about1800 m to 2100 m (6000 to 7000 ft) (Unruh and

Hector, 1999). Additional constraints on fault-fold geometry depicted by Unruh and Hector (1999) come from analysis of proprietary industry reflection data.

Geomorphic expression: There is no obvious expression of the Grizzly Island anticline as a line of hills or uplifted surfaces. The anticline is located in a marshy area that is barely above sea level.

Notes and References:

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

### 4.21 Potrero Hills thrust fault (blind)

Fault strand rank = 1

Location certainty = 2. Fault penetrated by gas exploration wells drilled in the northern Potrero Hills (Unruh and Hector, 1999).

Geomorphic expression: The Potrero hills comprise a fault-propagation fold in the hanging wall of the Potrero Hills thrust fault.

Notes and References:

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

### 4.22 Pittsburg-Kirby Hills Fault

Fault strand rank = 1

Location certainty = 1. Reaches of the Pittsburg-Kirby Hills fault are alternately well located and poorly located, depending on whether there is geomorphic expression of faulting and/or subsurface well control to evaluate deformation of key stratigraphic marker horizons. For example, the trace of the fault in the Sacramento River channel is associated with deformation of shallow strata imaged by high-resolution seismic reflection data (McCarthy et al., 1994). Constraints on the location of the fault also are provided by subsurface data from gas wells in the Kirby Hills. In general, the central trace of the fault between Van Sickle Island and Kirby Hills is most poorly constrained.

Geomorphic expression: The northwest-striking trace of the Pittsburg-Kirby Hills fault mapped by P. Williams south of the Sacramento River is associated with a modified southwest-facing slope break or scarp (P. Williams, personal communication, 2005). Recent paleoseismic trench investigations exposed tilted Quaternary bedding but no fault across the scarp, suggesting that the slope break is a modified fold scarp above a blind, northeast-dipping trace of the fault. Farther north, NNW-trending linear drainages and air photo lineaments in eastern Kirby Hill south of Nurse Slough are associated with traces of the Pittsburg-Kirby Hills fault (Unruh and Hector, 1999).

Notes and References: The Pittsburg-Kirby Hills fault is spatially associated with a north-northwest-trending alignment of deep earthquakes in the central Delta region (Ellsworth et al. 1982).

Ellsworth, W.L., Olson, J.A., Shijo, L.N., and Marks, S.M., 1982, Seismicity and active faults in the eastern San Francisco Bay region, *in* Hart, E.W., Hirschfield, S.E., and Schulz, S.S., 1982, Proceedings, Conference on Earthquake Hazards in the Eastern San Francisco Bay Area: California Division of Mines and Geology Special Publication 62, p. 83-92.

McCarthy, J., Hart, P.E., Anima, R., Oppenheimer, D., and Parsons, T., 1994, Seismic evidence for faulting in the western Sacramento Delta region: EOS (Transactions, American Geophysical Union), v. 75, p. 684.

Unruh, J.R., and Hector, S.T., 1999, Subsurface Characterization of the Potrero-Ryer Island Thrust System, Western Sacramento-San Joaquin Delta, Northern California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program award number 1434-HQ-96-GR-02724, 32 p.

Weber-Band, J., 1998, Neotectonics of the Sacramento-San Joaquin Delta area, east-central Coast Ranges, California: Ph.D. dissertation, University of California, Berkeley, 216 p.

### 4.23 Midland Fault (blind)

Fault strand rank: 1

Location certainty: 2. The Midland fault does not have a surface trace in the central Sacramento-San Joaquin Delta region. The fault was primarily identified and mapped by gas exploration geologists through subsurface correlation of stratigraphic units and analysis of seismic reflection data. Interpretation of borehole data suggests that sediments ranging in thickness from tens of meters to over a kilometer bury the tip of the fault (Arleth, 1968; Weber-Band, 1998). Map trace shown is from Jennings (1994), and is the subsurface trace compiled from numerous small-scale maps in the oil and gas literature (e.g., Krug et al., 1992). We checked the location of the Jennings (1994) trace by georeferencing published structure contour maps of the fault from oil and gas literature and comparing them to the digital Jennings trace. In general, there is good agreement, and we conclude that the Jennings (1994) trace is generally accurate at 1:24,000 and smaller scales.

Geomorphic expression: The Montezuma Hills in the central Delta region may be the surface expression of Quaternary reactivation of the west-dipping Midland fault as a reverse fault (Weber-Band, 1988). In this model, the Montezuma Hills are the uplifted hanging wall block of the Midland fault.

Notes and References: The Midland fault is a west-dipping fault along the eastern margin of the Montezuma Hills that accommodated extension and subsidence in the late Cretacous-early Tertiary Sacramento Valley forearc basin (Krug et al. 1992). Major west-down normal displacement on the fault ceased in Eocene time (e.g., Arleth, 1968; Krug et al., 1992), although minor normal displacement may have occurred in late Miocene time (Weber-Band, 1998). Seismic reflection profiles across the structure indicate that the dip of the fault is relatively steep at shallow depths and decreases with depth, indicating a downward-flattening, listric geometry. Based on detailed analysis of seismic reflection data, Weber-Band (1998) inferred post-late Miocene reactivation of the Midland fault to accommodate reverse slip and horizontal crustal shortening. The Thrust Fault Subgroup of the 1999 Working Group estimated that the long-term average late Cenozoic slip rate on the Midland fault ranges between 0.1-0.5 mm/yr (their preferred rate is 0.15 mm/yr).

Arleth, K.H., 1968, Maine Prairie gas field, Solano County, California, *in* Beebe, B.W., and Curtis, B.F., eds. Natural Gases of North America: American Association of Petroleum Geologists Memoir 9, v. 1, p. 79-84.

Krug, E.H., Cherven, V.B., Hatten, C.W., and Roth, J.C., 1992, Subsurface structure in the Montezuma Hills, southwestern Sacramento basin, *in* Cherven, V.B., and Edmondson, W.F., eds., Structural Geology of the Sacramento Basin: Volume MP-41, Annual Meeting, Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 41-60.

Weber-Band, J., 1998, Neotectonics of the Sacramento-San Joaquin Delta area, east-central Coast Ranges, California: Ph.D. dissertation, University of California, Berkeley, 216 p.

### 4.24 Conn Creek Anticline

Fault strand rank = 1

Location certainty, Conn Creek anticline axis = 1. Axis of Conn Creek anticline is well located at 1:24,000 scale based on strike-and-dip measurements of folded Neogene Sonoma Volcanics.

Location certainty, Conn Creek thrust fault = 3. Baldwin et al. (1998) infer that the Conn Creek anticline is a southwest-vergent fault-propagation fold formed above a blind, northeast-dipping thrust fault. Precise location of the tip line of the blind thrust fault is not known.

Geomorphic expression: The western limb of the Conn Creek anticline locally is overturned and forms the abrupt west-facing front of the Howell Mountains bordering eastern Napa Valley. The eastern limb of the anticline is expressed as well-developed dip slopes along Soda Canyon Road.

Notes and References:

Baldwin, J.N., Unruh, J.R., and Lettis, W.R., 1998, Neotectonic investigation of the northward extension of the Green Valley fault, Napa County, California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program Award no. 1434-HQ-96-GR-02738, 27 p. plus maps.

### 4.25 Glass Mountain Anticline

Fault strand rank = 2

Location certainty = 2. Anticline axis is approximately located at 1:24,000 scale based on a few scattered strike-and-dip measurements of folded Neogene Sonoma Volcanics.

Geomorphic expression: Anticline axis is associated with a northwest-trending ridge that flanks the eastern Napa Valley.

Notes and References: Given the short length of the Glass Mountain anticline and a possible right-stepping, en echelon relationship with the Conn Creek anticline directly to the southwest, it is possible that the Glass Mountain anticline represents local complications in the Conn Creek anticline as it dies out to the northwest.

Baldwin, J.N., Unruh, J.R., and Lettis, W.R., 1998, Neotectonic investigation of the northward extension of the Green Valley fault, Napa County, California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program Award no. 1434-HQ-96-GR-02738, 27 p. plus maps.

### 4.26 Bell Canyon Anticline

Fault strand rank = 2

Location certainty = 2. Anticline axis is approximately located at 1:24,000 scale based on a few scattered strike-and-dip measurements of folded Neogene Sonoma Volcanics.

Geomorphic expression: Anticline axis is associated with a northwest-trending ridge that flanks the eastern Napa Valley.
Notes and References: Given the short length of the Bell Canyon anticline and a possible right-stepping, en echelon relationship with the Glass Mountain and Conn Creek anticlines to the southwest, it is possible that the Bell Canyon anticline represents local complications in the Conn Creek anticline as it dies out to the northwest.

Baldwin, J.N., Unruh, J.R., and Lettis, W.R., 1998, Neotectonic investigation of the northward extension of the Green Valley fault, Napa County, California: Final Technical Report submitted to the U.S. Geological Survey, National Earthquake Hazards Reduction Program Award no. 1434-HQ-96-GR-02738, 27 p. plus maps.

### 4.28 Gordon Valley Segment, Great Valley Thrust Fault

Fault strand rank = 1

Location certainty =2. O'Connell et al. (2002) interpret that the tip line of the fault is at about 7 to 8 km depth beneath the range front based on interpretation of seismic reflection data, analysis of 3-D crustal velocity models, and elastic dislocation modeling of tectonic geomorphology. The branch line (i.e., intersection of the fault with the brittle-ductile transition) is interpreted to be at a depth of about 15 km (O'Connell et al., 2002). Both the tip and branch lines are included in the map database.

Geomorphic expression: East-facing front of the Vaca Mountains south of Putah Creek is the forelimb of a northeast-vergent fault-propagation fold formed above the blind Gordon Valley segment.

Notes and References: O'Connell et al. (2002) interpret that the Gordon Valley segment of the Great Valley thrust fault is the likely source of the 1892 Winters-Vacaville earthquake sequence.

O'Connell, D.R.H., Unruh, J.R., and Block, L.V., 2001, Source characterization and ground-motion modeling of the 1892 Vacaville-Winters earthquake sequence, California: Seismological Society of America Bulletin, v. 91, p. 1471-1497.

### 4.29 Trout Creek Segment, Great Valley Thrust Fault

Fault strand rank = 1

Location certainty = 2. O'Connell et al. (2002) interpret that the tip line of the thrust fault is at about 8 to 9 km depth beneath the range front based on interpretation of seismic reflection data, analysis of 3-D crustal velocity models, and elastic dislocation modeling of tectonic geomorphology. The branch line (i.e., intersection of the fault with the brittle-ductile transition) is interpreted to be at a depth of about 15 km (O'Connell et al., 2002). Both tip and branch lines are included in the map database.

Geomorphic expression: East-facing front of the Vaca Mountains between Putah Creek and Capay Valley is the forelimb of a northeast-vergent fault-propagation fold formed above the Trout Creek segment.

Notes and References:

O'Connell, D.R.H., Unruh, J.R., and Block, L.V., 2001, Source characterization and ground-motion modeling of the 1892 Vacaville-Winters earthquake sequence, California: Seismological Society of America Bulletin, v. 91, p. 1471-1497.

## 5.0 REFERENCES


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Crane, R.C., 1995, Geology of the Mt. Diablo region and East Bay hills, *in* Sangines, E.M., Andersen, D.W., and Buising, A.V., eds., Recent Geologic Studies in the San Francisco Bay Area: Society of Economic Paleontologists and Mineralogists, Pacific Section v. 76, p. 87-114.

Jayko, A.S., and Lewis, S.D. (Principal Compilers), 1996, Toward assessing seismic risk associated with blind faults, San Francisco Bay Region, California: U.S. Geological Survey Open-File Report 96-267, 188 p.

Suppe, J., and Medwedeff, D.A., 1984, Fault-propagation folding: Geological Society of America Abstracts with Programs, v. 16, p. 670.

Thrust Fault Subgroup, 1999, Report on Thrust Fault Sources to the Working Group on Northern California Earthquake Probabilities: compiled and submitted by J.R. Unruh, William Lettis & Associates, Inc., 21 p.

Unruh, J.R., 2001, Characterization of Blind Thrust Faults in the San Francisco Bay Area, *in* Ferriz, H. and Anderson, R., Engineering Geology Practice in Northern California": California Geological Survey Bulletin 210, p. 211-227.

Working Group on Northern California Earthquake Probabilities, 1999, Earthquake probabilities in the San Francisco Bay region: 2000 to 2030 - A summary of findings: U.S. Geological Survey Open-File Report 99-517.